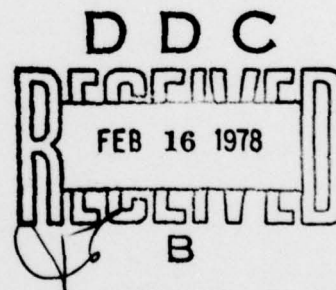(12)

TECHNICAL REPORT #12

ACTIVATION AND SUSTAINED ATTENTION:

A PUPILLOMETRIC STUDY OF AN AUDITORY VIGILANCE TASK

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Using a classical auditory vigilance task, the relations between pupillometric indices of phasic central nervous system increases in activation and sustained attention were investigated. The amplitude of the task-invoked pupillary response declined as a function of time in task at a rate paralleling the performance decrement. These findings are discussed in the context of an activation theory of attentional processes.

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INTRODUCTION

The study of sustained attention in man is virtually defined by an experimental paradigm, the vigilance task (Jerison, 1977) in which an observer is required to monitor a single display for prolonged periods to detect infrequent targets against a background of frequent nontarget signals. Under such conditions, performance normally deteriorates as a function of time on task, an effect that has been termed the "vigilance decrement." This decrement is usually attributed to a gradual decline in the level of central nervous system activation (Mackworth, 1969; Stroh, 1971; Mackie, 1977). Support for the activation theory of sustained attention comes primarily from experiments demonstrating that degraded performance in a vigilance task is associated with physiological signs of decreased activation.

Electroencephalographic (EEG) indicators of central nervous system activation have been investigated in vigilance tasks by several groups. Haider, Spong and Lindsley (1964), for example, were able to demonstrate that the amplitude of cortical event-related potentials (ERPs) declined with detection efficiency as a function of time on task. Further, ERPs to undetected targets were smaller than ERPs to detected targets, suggesting that detection failure is associated with activation-related lapses of sustained attention. Studies of changes in the spontaneous EEG rhythms in vigilance tasks also lend support to an activation theory of sustained attention. In particular, the presence of theta frequency (3 to 7 Hz) activity in the posterior EEG, an electroencephalographic sign of drowsiness (Rechtschaffer & Kales, 1968), often increases as performance deteriorates in vigilance-type tasks. Such effects have been reported by Oswald (1962), Williams et al. (1962), Groll (1966), and O'Hanlon and Beatty (1977). Beatty, Greenberg, Deibler, and O'Hanlon (1974) were also able to demonstrate that when operant conditioning procedures are employed to control posterior theta frequency activity during a vigilance task, operant suppression of theta activity abolishes the vigilance decrement whereas operant augmentation of theta activity increases the magnitude of the decrement, providing an experimental test of one aspect of the activation theory of sustained attention.

The major difficulty with the activation theory of sustained attention, as it is presently formulated, is that it falsely simplifies the complex nature of brain activation processes. For example, the original concept of the brainstem reticular formation as an undifferentiated, diffuse network that regulated the level of brain activation is no longer tenable. The anatomy of the brainstem activating systems is now known to be highly complex and intricately organized (Schlag, 1974). Physiologically, the effects of activation are also more complicated than was initially realized (Duffy, 1972). Similar

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complexities have appeared in studying the neurophysiological basis of sustained attention. Not all physiological indicators of activation appear to decrement in the vigilance task (Jerison, 1977); only indicators of activation appear to be related to sustained attention. Therefore, by analyzing the pattern of physiological activation that affects performance in the vigilance task, the physiological basis of sustained attention might be identified. The activation theory of sustained attention must then be modified to do justice to the complexity of the neuropsychological data.

One approach to this question may come from the analysis of different classes of physiological indicators of central nervous system activation, such as the movements of the pupils of the eye. The study of pupillary movements played a major role in the initial analysis of reticular activating system (Moruzzi, 1972). Recent technical advances have made pupillometric analysis a feasible approach to the study of brain activation and behavior in man.

Pupillary Signs of Brain Activation.

Pupillary diameter is determined by the relative excitation of the two muscle systems of the iris, the radially-oriented sympathetically-innervated dilator pupillae and the parasympathetically innervated sphincter pupillae. Thus, pupillary dilations result from either sympathetic activation or parasympathetic inhibition alone, or both factors in combination (Loewenfeld, 1958).

It is useful to distinguish two types of pupillary movements which differ in their temporal properties: the very short latency and short duration phasic responses and the much slower tonic pupillary movements, the durations of which may be measured in minutes or hours. In a wide variety of cognitive tasks, phasic pupillary responses appear to be closely related to momentary changes in information processing load (Goldwater, 1972). For example, phasic pupillary dilations are observed as items are stored in memory for immediate recall, the magnitude of the dilation being a nearly linear function of the number of items stored (Kahneman & Beatty, 1966). Similarly, in a perceptual discrimination task, the amplitude of the phasic pupillary response is a direct function of discrimination difficulty. These transient, processing-related dilations appear to be independent of tonic or baseline pupillary shifts (Kahneman & Beatty, 1967).

Changes in tonic pupillary diameter have been related to changes in alertness and fatigue. Yoss, Moyer and Hollenhorst (1970), in a study of narcoleptic patients, report that tonic pupillary diameter decreases by 50

percent between full wakefulness and the onset of sleep. Further, a rapid dilation of similar magnitude is observed when the sleeping patient is awakened. This dilation is then maintained if the patient remains alerted.

Fatigue may also be reflected in tonic pupillary diameter. Peavler (1974) reports an attempt to assess the fatiguing effects of two different working procedures in a group of telephone operators. Pupillary diameter was measured at the beginning and at the end of an 8-hour work period using both working procedures. A larger and statistically more reliable decrease in pupillary diameter was observed in the operators when using the subjectively more fatiguing procedure. Lowenstein and Loewenfeld (1952) had previously reported a decrease of 1 to 1.5 mm in pupillary diameter over an 8-hour work period which they considered to be an autonomic sign of central nervous system fatigue.

Finally, tonic pupillary diameter has served as an indicator of physiological arousal in a series of acute animal experiments investigating the organization of brainstem activating systems, with full pupillary dilation indicating high physiological arousal (Moruzzi, 1972).

Thus, pupillary movements may reflect two aspects of brain activation. Phasic responses appear to be closely related to the demand imposed by ongoing cognitive processes, whereas tonic changes appear to reflect more global shifts in organismic activation. Since previous work has indicated that these two components of activation may be somewhat independent of each other (Kahneman & Beatty, 1967), the study of pupillary responses might be useful in clarifying the nature of the activation processes that appear to underlie sustained attention. To obtain such data, the following experiment was performed.

METHOD

Subjects.

Eleven persons served as subjects; three were members of the laboratory and eight were university students who were paid $2.30/hr for their services. Three of the subjects were males.

Experimental Environment.

Each subject was tested individually in a sound-attenuated experimental chamber. Acoustic white noise was presented over a loud speaker in the

chamber to further mask extraneous noise originating in adjoining rooms.

Stimuli.

A string of 1 kHz 50 msec tone bursts were presented every 3.2 sec. Tone bursts were generated by a Hewlett-Packard 200AB audio oscillator, electronically switched, amplified, and presented to the subject over binaural earphones. Target tones were attenuated by -3.5 db.

Task.

Each subject was required to monitor the auditory display and report any targets detected by depressing a microswitch. The test was 48 minutes in duration, divided for purposes of analysis into nine segments of 5 minutes 20 seconds, each containing 12 target and 88 non-target stimuli. Subjects were given practice exposure to both kinds of stimuli before testing.

Experimental Control.

The entire experiment was controlled by a general purpose laboratory computer (Hewlett-Packard 2116B), including stimulus presentation, data acquisition, data editing and data analysis.

Pupillometric Measurement.

Pupillary diameter was measured on-line in the experiment using a Whittaker 1050S TV pupillometer. This device processes the image obtained from an infrared video camera, identifies the pupil using a specialized pattern-recognition algorithm, and computes the diameter of the image of the pupil. Pupillary diameter is transmitted to the computer as an analog signal and the processed image of the eye with an indication of the machine-identified pupil is displayed to the experimenter to assure that the pupillometer is providing accurate measurements; the experimenter could reject on-line pupillometric data that was inaccurately measured.

To obtain accurate pupillometric measurements over a prolonged period without interruptions the following procedures was employed. The subject sat in a comfortable upright chair and rested both chin and forehead on a Bausch and Lomb head rest. The video camera was positioned 15 cm from the subject's left eye and angled 35° to prevent interference with the sub-

ject's field of view. A television monitor displaying the image of the eye at very low contrast was positioned 1 m from the subject in the center of the visual field to enable him to maintain a stable position in the pupillometer for the duration of the task.

Data Acquisition.

Pupillometric data was sampled at 50 msec intervals and stored as time-series data on disc for later analysis. For analysis purposes, data was stored in 6.2 sec trials, with stimuli presented at 0 and 3.2 sec in each trial. No data was taken between 6.2 and 6.4 sec, during which time the control program performed other functions. Thus the data from each of the 9 segments of the experiment was stored as 50 6.2 sec trials. The 12 targets of each segment were always presented as the second stimulus of each trial. The knowledge that signals would appear on only even numbered signals was of little use to the 3 subjects who were acquainted with the experimental procedures, and was unnoticed by the 8 paid subjects. This permitted the differential analysis of the pupillary response to the non-target stimulus preceding detected and undetected target stimuli. Behavioral data on detection responses was also stored on disc for later analysis.

Data Editing.

The digitized pupillary record of each trial was individually examined on a cathode-ray tube display after the experimental session. Trials were either accepted if no artifacts were present, edited if flawed by minor artifacts or rejected if contaminated by major artifacts. Editing was accomplished using a linear interpretation algorithm between uncontaminated data points on either side of the eyeblink or pupillometer artifact. If the artifact was in a critical region of the trial, during or immediately following presentation of either of the two stimuli, or was greater than about 500 msec in duration, the trial was rejected. Editing of the pupillometric data was blind with respect to both stimulus and response conditions. Across all subjects, 19 percent of all trials were rejected. The probability of trial rejection increased as a function of time in task, rising from 12 percent in the first third of the experiment, to 20 percent in the second and 25 percent in the final third. This increase in rejection rate is highly significant, as indicated by an analysis of variance ($F(2, 20) = 7.270$, $p < .005$). However, there is no evidence to indicate that target and nontarget trials were differently affected.

Data Analysis.

Pupillometry.

After editing, the averaged pupillary response was computed in each of the nine segments of the test for nontarget trials, trials with missed targets and trials with correctly detected targets. From these primary averages, six secondary averages were computed for each subject. The averaged pupillary responses to non-target stimuli by thirds of the test (segments 1, 2 and 3; 4, 5 and 6; 7, 8 and 9) were computed to test for the effects of time on task upon pupillometric measures. To test for the relations between pupillometric measures and performance, pupillary responses were averaged over all segments containing at least one hit, miss and nonsignal trial separately for each stimulus/response category. Tonic and phasic measures of pupillary activity were then computed from these averaged pupillary responses. Tonic pupillary diameter was estimated as the value of the pupillometric record at the onset of the second stimulus. Phasic pupillary response was computed as the maximal pupillary dilation in the 1.5 sec interval following presentation of the second stimulus. An analogous phasic pupillary measure was computed for the first stimulus in an analysis of differential responsiveness preceding detected and undetected targets.

Performance.

The performance of each subject was characterized by the percent correct detections in each segment of the experiment. These values were then averaged to obtain percent correct detections scores for each third of the vigilance test. False alarms, although infrequent (16 percent of all responses) were similarly analyzed.

RESULTS

Performance.

The probability of correctly detecting a target declines systematically over thirds of the vigilance test, dropping from 83 percent in the first period to 73 percent in the middle period and to 69 percent in the final period of the task (see Figure 1). This performance decrement is highly systematic and reliable, as indicated by analysis of variance (ANOVA) ($F_{(2, 20)} = 9.403$, $p < .005$). The degree of performance decrement was also analyzed by computing the slope of the linear function relating percent correct detection and period of the task. By this analysis eight subjects showed performance decrements and three did not.
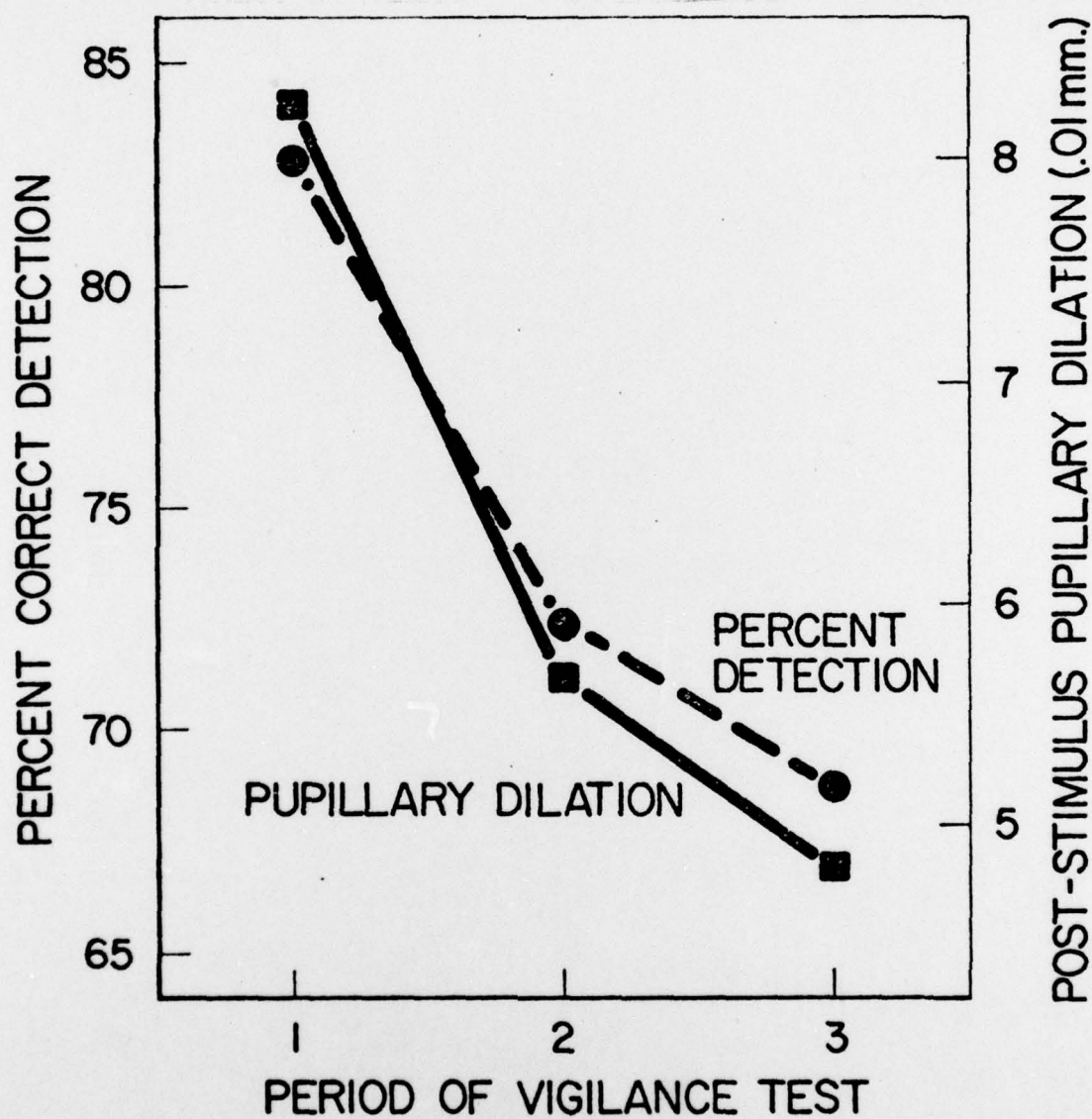
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FIGURE 1

Figure 1. Percent targets correctly detected (circles) and mean pupillary dilation to nontarget stimuli (squares) averaged over eleven subjects as a function of period of task. Both measures change in a similar manner during the vigilance task.

Whether this performance decrement reflects a loss of sensitivity or a shift in response bias (Green & Swets, 1966) is not clear, as false alarms also decreased as a function of time on task. Although these rates were quite low (.03, .02, and .01 percent in the three periods of the experiment), the decline was highly significant ($F_{(2,20)} = 9.721$, $p < .005$).

Pupillometry.

Tonic pupillary diameter (estimated as pupillary diameter at the onset of the second stimulus in a trial) did not vary significantly over periods of the task, as tested by analysis of variance ($F_{(2,20)} = .048$, N.S.). Nor did any of several other estimators of tonic pupillary level yield a significant effect.

However, the amplitude of phasic pupillary dilations in response to task-relevant stimuli did decline systematically as a function of time on task, in a manner that closely paralleled the decrement in performance (see Figure 1). The maximum pupillary dilation in the 1.5 sec period following the onset of the nontarget stimulus declined significantly over thirds of the task, as tested by analysis of variance ($F_{(2,20)} = 5.235$, $p < .01$). Figure 2 presents the evoked pupillary response waveforms for nontarget stimuli for the three periods of the task.

For target trials, the phasic pupillary response to target stimuli differed significantly for detected and undetected targets by t-test ($t_{(10)} = 4.000$, $p < .01$). Figure 3 presents the evoked pupillary response waveforms for both detected and undetected targets over all periods of the task. The phasic pupillary response for detected targets is more than twice as large as the response to undetected targets. However, detected and undetected targets do not differ significantly in baseline pupillary diameter at stimulus onset ($t_{(10)} = .152$, N.S.).

An attempt was also made to predict detection of target stimuli by analysis of the pupillary response to the immediately preceding non-target stimulus. However, neither phasic dilation nor tonic baseline differed significantly between nontarget stimuli preceding detected and undetected targets.

To assess the strength of the relationship between phasic pupillary activity and performance, a correlation was computed for each subject between percent targets detected in each 5 minute 20 sec block and the amplitude of the dilation to nontarget stimuli in that block over the nine blocks of the experiment. For the three subjects who did not show a performance decrement
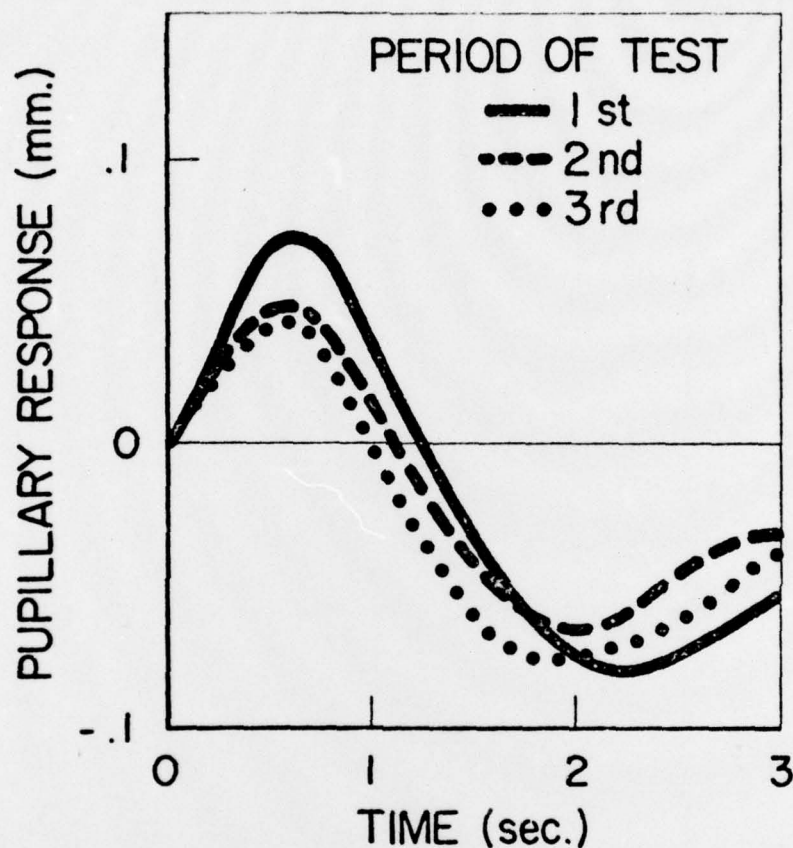
FIGURE 2

Figure 2. Averaged evoked pupillary responses to non-target stimuli for the first, second and third period of the vigilance task. Differences in peak dilations are highly significant.

over time in the task, the mean correlation between dilation and performance was +.01 (range: -.19 to +.24). For the eight subjects in which performance deteriorated over time all correlations were positive. The mean value of the correlation was .41 (range: +.14 to +.77).
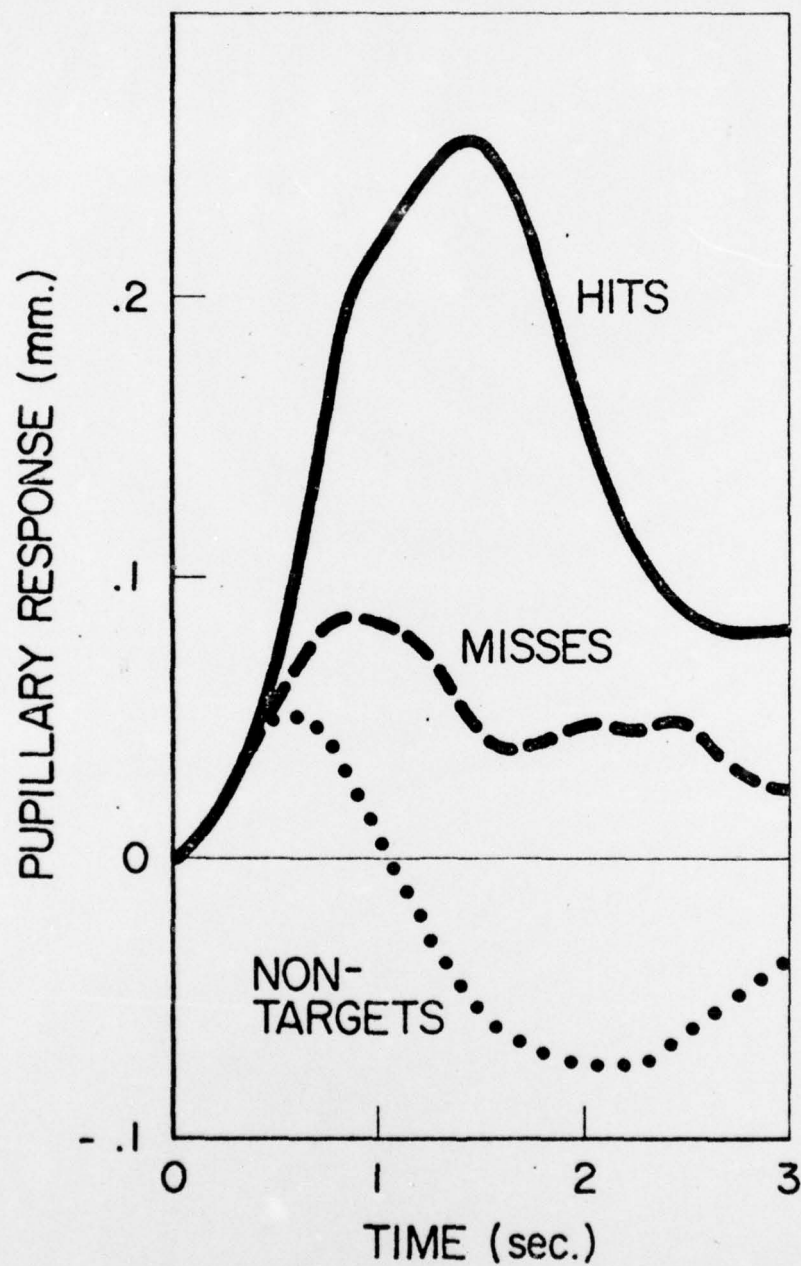
FIGURE 3.

Figure 3. Averaged evoked pupillary response for nontarget stimuli, and for detected and undetected target stimuli.

DISCUSSION

Although tonic pupillary diameter decreases markedly between wakefulness and the onset of sleep (Yoss, Moyer, & Hollenhorst, 1970) and decreases over an 8-hour work period (Lowenstein & Loewenfeld, 1952), the extent of that decrease being greater after subjectively more fatiguing work (Peavler, 1974), tonic pupillary diameter is not related to performance in the auditory vigilance task employed in this experiment. In contrast, the amplitude of the phasic pupillary response to task-related stimuli did decrease in a manner paralleling the performance decrement. Such pupillary changes have been previously shown to be systematically related to performance characteristics in a variety of information-processing tasks. In these contexts, pupillary dilations have been taken as a sign of attention (Beatty, 1977) or "effort" (Kahneman, 1973). The present experiment extends this relation to include vigilance tasks. These data suggest that the behavioral processes of both intensive and sustained attention might share a common physiological basis. However, the apparent dissociation between sustained attention and tonic arousal level deserves further explication.

Mention should also be made of the difference in the evoked pupillary response to targets that were detected and targets that were missed. Although the larger dilations observed in the former case might to some extent reflect differences in predecisional processing of the auditory signal, the fact that a behavioral response was required only for detected targets suggests a simpler alternative. The large magnitude dilations observed for detected targets probably reflects activation associated with response organization and execution (Kahneman, 1973). Similar response effects have been previously reported in other experimental tasks (Paivio, 1973).

The dissociation between phasic and tonic pupillometric measures of central nervous system activation observed in the present experiment indicates that a detailed analysis of the relations between activation and attention is necessary. One attempt in this direction has been published recently by Pribram and McGuinness (1975). The strength of the empirical relations between activation measures and performance variables observed here and elsewhere (Kahneman, 1973; Beatty, 1976, 1977) bode well for the ultimate success of an activation theory of attention.

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